

Martian Aerobot Missions: First Two Generations

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Abstract - Role of aerobot missions as a new vehicles for Mars exploration have been emphasized at the recent NASA Workshop on Concepts Recent and Approaches for Mars Exploration (Houston, July 2000). Unique combination of proximity to the surface and mobility (exceeding tens of thousands of kilometers) with elimination of the landing makes aerobots a vital component of Mars investigation.

The recent progress in the multi-center JPL-lead Mars Balloon Validation Program (MABVAP)⁽¹⁾ provides a foundation for feasible planetary aerobot missions; it revealed also risks associated with them. Risks of the previously proposed large-scale Mars balloon missions (Russian-French Mars Aerostat⁽²⁾, Mars Aerial Platform (MAP) proposal⁽³⁾ and Mars 2001 Aerobot/Balloon Study (MABS)⁽⁴⁾ were too high to be realized at that time.

The proposed approach is to develop the first generation of the small-scaled focused science missions that do not impose excessive requirements on the balloons, entry, deployment and inflation system (EDI), materials, instrumentation and communication. Such mission may provide an exceptional focused science data and validate key technologies that

would enable the next generation of more capable missions. The paper describes implications of Martian atmospheric and surface conditions on balloon mission performance. The first missions should operate in the relatively benign environments of mid-season and near the poles; they are of a micromission class with mass of entry vehicle 35-60 kg and could be launched as an auxiliary or piggy-back payload.

Required miniaturization of payloads need use of technologies developed for other micro vehicles such as nano-rovers. Flexible power and CD&H management may adjust science and technology requirements to the limited payload resources. Light-weight low-power communications system with a capable relay infrastructure are essential for data return of the aerobot missions.

The next generation of aerobots with mass of entry vehicle 150-200 kg will deliver aerobots with payloads 10-20 kg that will carry a complex of science instruments that will support a number of observations of surface and atmosphere. A part of payload could be used to install a power train (motors with propellers) to provide a degree of trajectory control by steering the aerobot in the desired direction.

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1. INTRODUCTION

Increasing of mobility of vehicles for in situ study of Mars is one of priorities of the Mars exploration program. Range of present-day landers and rovers is tens of meters, range of future rovers would be units or tens of kilometers. Aerial vehicles may cover from thousands to hundreds of thousands of kilometers at the areas inaccessible for surface vehicles. During the flight they could provide data (imaging, IR, magnetic, radar, gamma-ray, neutron etc.) with resolution and sensitivity of orders of magnitude better than from orbiters.

Two classes of aerial vehicles – heavier-than-air (HTA - airplanes and gliders) and lighter-than-air (LTA - balloons, blimps) differ substantially. HTA may carry heavier payload and have capability of trajectory control; their weaknesses are short endurance (few tens of minutes now and hours in future), difficulties of data transmission (need synchronization and orbiter antenna pointing to download data while in flight) and high speed (100-150 m/s) which limits resolution of measurements.

There are many different types of LTA: passive - conventional light-gas zero-pressure balloons, balloons with guiderope, zero-pressure solar heated balloons (montgolfieres), light-gas superpressure balloons, and powered - blimps and dirigibles. Without expendable materials (buoyant gas or ballast) the lifetime of zero-pressure balloons is limited by 6-12 hours for solar montgolfieres and 18-20 hours for light-gas balloons. Lifetime of the super-pressure balloons is limited by the gas leakage and its theoretical limit, which is controlled by diffusion, may be several years. Without propulsion, balloons drift with the wind and have no ability of trajectory control. An indirect control may be achieved by changing altitude to pick up winds at the other level; to be effective it requires a detailed knowledge of the actual wind system which is not the Mars case.

True for
Endurance, surface coverage and well predictable flight profile make the superpressure balloons a vehicle of choice for meaningful science missions. The considerable effort in the The probe on-going JPL-lead Mars Balloon Validation Program (MABVAP) is directed to develop a technology to the level acceptable for the Mars missions.

In distinction with the previous efforts (Russian-French Mars Aerostat project⁽²⁾, Mars Aerial Platform Discovery proposal⁽³⁾, Mars Aerobot Study⁽⁴⁾) which suggested to use large balloons that in turn required heavier spacecrafts and costly missions, the present approach is to develop at first a smallest possible vehicle with a focused science payload that could be implemented in a low-cost mission. At the next phase, after collecting data and acquiring experience of flights on Mars, bigger balloons with more comprehensive sets of instruments could be realized.

2. FLIGHT ENVIRONMENT

Low air density and big daily surface temperature variations (that control IR fluxes) are major challenges for ballooning on Mars. On the other hand, heavier carbon dioxide provides 50% increase of buoyancy of gas in comparison to the Earth's air. As well known, Balloon is a thermal vehicle which is controlled by radiative fluxes. In a free flight conditions on Mars the convection between the balloon envelope and ambient atmosphere is small and temperature of balloon envelope (and gas inside) can be determined from a thermal balance equation⁽⁵⁾

$$T = \{1/(\epsilon\sigma) * [\alpha (Q_s + Q_r + Q_d) + \epsilon (Q_{iru} + Q_{ird})]\}^{1/4}$$

where σ – Stefan-Boltzman constant, α and ϵ are solar absorptivity and infrared emissivity of the envelope, Q_s , Q_r and Q_d – direct, upward (reflected) and downward (scattered) solar fluxes on the balloon, Q_{iru} and Q_{ird} – upward and downward infrared fluxes.

All the fluxes vary with a season, local time and latitude. All solar fluxes depend on amount of dust in the atmosphere and Q_r – on the albedo of the surface. The upward IR flux is controlled by the surface temperature; during the daytime it is defined by thermal balance of surface with the downward solar flux. During the night it depends on thermal inertia of upper layers of soil. The downward IR flux is small and does not vary significantly. Such environment results in variations of thermal loads on the balloon significantly higher than on Earth where the daily variations are smoothed by an IR radiation of the atmosphere.

Combination of low atmospheric density with large daily variations of radiation fluxes makes ballooning on Mars especially challenging. Low

density requires large size balloons. Variation of radiation fluxes affects the temperature of balloon envelope and temperature of buoyant gas which expands during daytime heating and compresses during night-time cooling.

If balloon envelope is open and pressure of buoyant gas is equal to ambient pressure (zero-pressure balloons), then gas vents during day and amount of gas remained is insufficient to keep balloon afloat during night without dropping ballast or using guiderope to compensate deficit of lift. Temperature variations of balloon depend on season, location and envelope material properties. In the extremes they may reach 30-50% and accordingly 30-50% of the total floating mass (which include balloon, payload and buoyant gas) should be dropped each night (or brought to the surface as guiderope) in order to survive for the next day. It limits lifetime of zero-pressure balloons to 1-2 days for ballast dropping or by time when the guiderope will snag while dragging over the surface.

Superpressure balloons have closed envelope and pressure inside the balloon exceeds the ambient pressure. Balloon keeps up constant volume and floats at constant density level. This level, if it is not too close to the Martian surface, preserves almost constant altitude above the reference ellipsoid and the balloon floats at almost constant altitude. Maximum lifetime is limited by buoyant gas loss by diffusion through envelope and exceeds hundreds of days. Practical lifetime is limited by and leakage through imperfections in the balloon (pinholes, seams, and fittings). Earth experience shows that it may also reach hundreds of days. Penalty is necessity to use strong materials that will not break under the day-time increase of pressure inside the balloon. The necessity of combination of light weight with high strength is a challenge for superpressure balloon materials and for superpressure balloon design.

Another action of the temperature is change of properties of the envelope material which become weaker with increase of temperature. Materials that are transparent to the solar radiation (i.e. that have a small α) would exhibit minimum temperature variations. Balloon material should possess a set of contradictory properties: light areal density, high strength, low permeability, wide range of operating temperatures.

In long-duration flights (over hundreds of days) the balloon may appear in any season and at any site and ideally it should withstand loads independent of season or location. In future it could be the case with progress in materials, balloon designs and heavier entry vehicles. For the first missions the requirements may not be so restrictive, the lifetime and location could be selected to make possible a safe mission within capabilities of current technology and available budget. This philosophy was base for the Piccard proposal submitted for a current cycle of Discovery missions. In the subsequent text it will serve as an example of a small-scale Phase 1 mission.

The mission will imply the comparatively small spherical superpressure balloon to carry the payload with magnetometer in 2005 mission opportunity. The balloon has diameter 11.5 m made of 8 mm Mylar film and is filled with hydrogen.

Two factors are beneficial for success of the mission. Firstly, 2005 mission opportunity and the selected mapping area (35-55S, 180-210E) provide favorable environment: it is near fall equinox at the Southern hemisphere after the dust storm season, when atmospheric pressure, solar radiation and temperature variations are near their average. Secondly, payload mass is small – less than 2 kg – that makes possible use of relatively small balloon. Smaller balloon size decreases implementation risks since stress in material and deployment loads increase with balloon diameter. It allows to use proven materials and fabrication methods and reducing costs of the mission.

Nominal float altitude should provide a sufficient clearance above the local topography in presence of balloon vertical motions. Though in general the Southern hemisphere is more elevated and less favorable for balloon flight than the Northern hemisphere, in the mission mapping area (30-50 S 150-210E) the surface elevations are moderate and do not exceed 3000-3400 m above the reference ellipsoid. During daytime convective heating of the atmosphere lowers the constant density surface and the floating height. According to the Ames Research Center General Circulation Model (GCM) ⁽⁶⁾ for night-time floating altitude 1100 m the daytime altitude decrease by 500 m to 630 m. This effect rapidly decreases with height and the altitude changes only ~ 75 m for floating altitude 2800 m above

the surface. Another effect is variations of the altitude under vertical air motions, which will be illustrated later. Floating altitude 6000-7000 m above reference ellipsoid (11.2 g/m^3) provides sufficient clearance above the local terrain (2600-3600 m).

3. BALLOON TRADES

Size and mass of the balloon are driven by several factors: payload mass, flight altitude and ambient air density, daytime superpressure, yield strength and areal density of film. Balloon diameter, floating mass and yield stress as function of film thickness for float altitude 7 km and payload mass 2 kg are shown in Fig.1. Both floating mass and balloon size grow rapidly

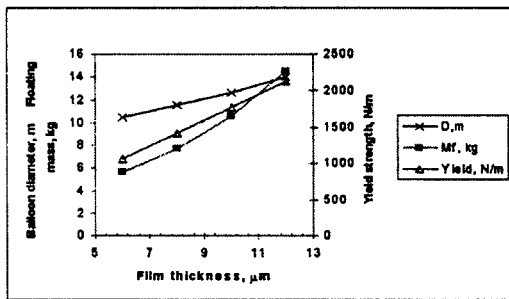


Fig.1. Balloon diameter, floating mass and yield strength as function of Mylar film thickness

with increase of film thickness. Fig.2 shows balloon diameter and total floating mass as

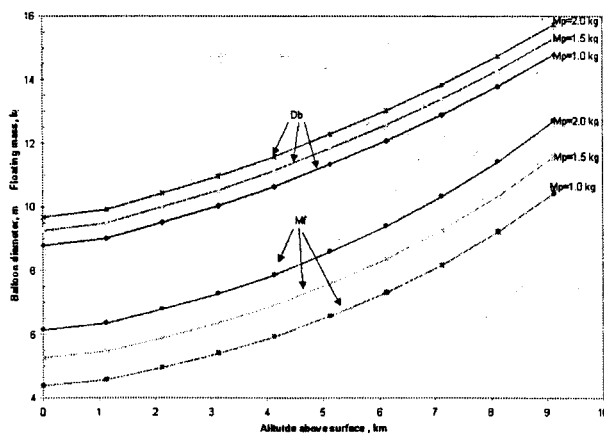


Fig.2. 8-μ Mylar balloon diameter and floating mass as function of altitude above surface.

function of floating altitude for payload mass from 1 to 2 kg and 8 μm Mylar film.

Superpressure and operating film stress are controlled by difference of day and night balloon temperatures and by mass of buoyant gas. With known thermo-optical properties of film, the day-time and night-time balloon temperatures were determined from radiative-convective equilibrium with solar and infrared fluxes from the GCM model for appropriate season and location. Mass of buoyant gas is determined to ensure positive night-time superpressure that influence life-time, sufficient free lift after balloon inflation and safety factor >1.5 during diurnal cycle.

4. BALLOON FLIGHT PROFILE

Flight performance of the balloon in the Martian environment was simulated in the integrated model which includes the GCM data on temperature, solar and infrared heat fluxes as function of local time and altitude for appropriate season and latitudes, aerodynamic and thermal model of the balloon, change of the yield strength with temperature, gas leakage, change of balloon size with superpressure and temperature, eventual atmospheric turbulence etc.. Flight simulations were performed mostly for latitude 30S which is the worst case from point of view of thermal and mechanical loading on the balloon.

Possible holes in envelope limit the flight endurance. To estimate this effect the simulations were performed for holes sizes from 0.1 mm (pinhole) to 10 mm; one case was run for intermediate hole 0.7 mm that was actual size of hole in the free flight of full-scale CNES Mars Aerostat prototype (volume 5500 m³) made of 6 μm Mylar film. Some results are shown in Fig.3-5 (in the charts, all altitudes are above the

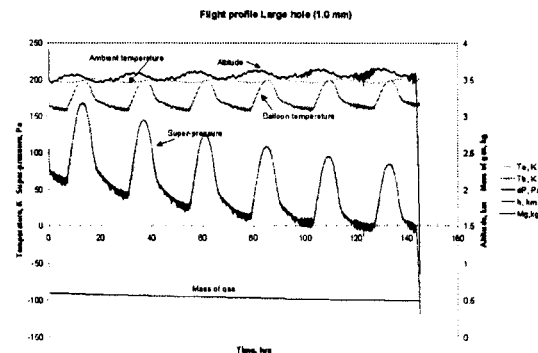


Figure 3. Balloon flight profile 1-mm diameter

surface level). The results indicate that single pinholes do not limit the balloon lifetime. Even with the large hole that can be detected during the fabrication tests balloon will be afloat for 4-6 days.

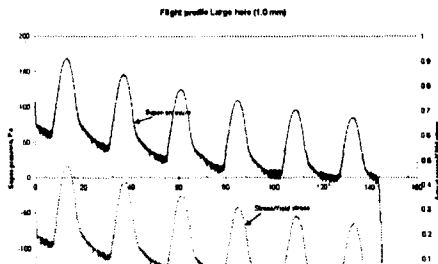


Figure 4. Temperature and superpressure during flight (1 mm diameter hole)

In the steady flight the balloon maintains almost constant altitude (daily variations are within 200-300 m). Daily cycle of the balloon temperature and superpressure are clearly pronounced. Night-time superpressure decreases due to gas leakage and balloon descends to the surface when superpressure approaches zero and remaining mass of gas is not enough to provide neutral buoyancy (negative values of superpressure in Fig. are artificial and rather indicate the negative lift). It is worth to mention that the maximum floating altitude increases slightly with gas leakage since the floating mass decreases. Fig. 4 shows ratio of the actual stress to yield stress (reciprocate to the safety margin); its maximum value is ~ 0.5 (i.e. safety margin 2) at the first day and decreases with drop of superpressure in the following days.

Effect of atmospheric turbulence is demonstrated in Fig. 5 which shows balloon behavior under hypothetical vertical wind varying from +3 to -3 m/s (comparable to vertical motion in *cumulus* or thunderstorm clouds on Earth). Maximum altitude variations of the balloon are ± 350 m. Superpressure variations are less than ± 20 Pa.

5. ENTRY, DEPLOYMENT AND INFLATION

As landing is the most critical part of lander or rover missions as the deployment and inflation is the most critical part of the balloon mission. A probe descend time on Mars is counted in minutes. It imposes requirement of rapid deployment and inflation of balloon and leads to

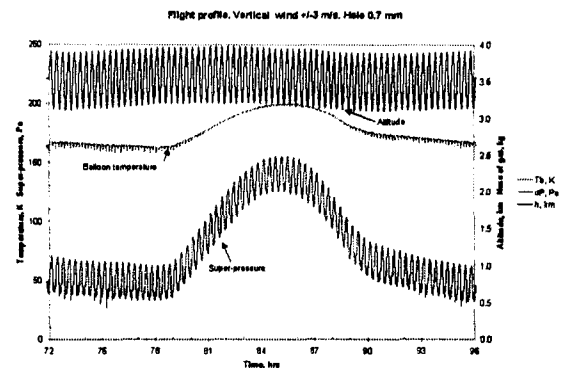


Figure 5. Balloon flight profile under vertical wind of 3 m/s amplitude

shock loads and aerodynamic loads on thin film of its envelope. Complexity of the interaction of between the light flexible membrane and non-steady aerodynamic forces makes difficult if not impossible, accurate simulation of the process. The on-going Mars Balloon Validation Program addresses this problem and made substantial progress in development of the technology.

Typical entry, deployment and inflation sequence is shown in Figure 6. The probe will

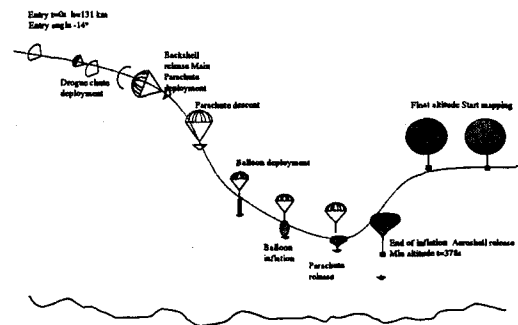


Figure 6. Entry, deployment and inflation sequence

enter the atmosphere at angle -12 deg. A small supersonic parachute will be deployed by a mortar at $M=1.8$ (altitude $\sim 10,500$ m). When velocity of the entry vehicle will decrease to $M\sim 0.7$, the backshell will be released and the main subsonic parachute will be deployed from its deployment bag. The heatshield will be released simultaneously.

After approximately 10 s descent on the main parachute the balloon container will be opened and balloon will be deployed. Shock load core

inside the balloon and the ripstitch located between the parachute and balloon will mitigate deployment shock.. The balloon inflation will start in 10-20 s after the deployment. The inflation will be completed in ~ 100 s and the inflation system will be released. The main parachute will be released earlier. After release of the inflation system balloon will start to ascend. At the minimal altitude balloon will be 1500-1800 m above the surface. Balloon will reach the floating altitude ~7000 m in 10-15 min. The technology of aerial deployment and inflation is under the stratospheric tests in the MABVAP program.

6. MARTIAN AEROBOTS OF NEXT GENERATION

Experience accumulated in implementation of the first small-scale Martian aerobot missions will be a base to develop the next generation of more capable aerobots with payload mass 10-20 kg. The payload may include a set of instruments for a multi-discipline surface characterization.

Almost ideal vertical orientation during the free flight makes the aerobots especially beneficial for carrying large light weight radar antennas or radiators for electromagnetic sounding. It is quite feasible to develop inflatable linear, loop or array antennas with size of 10-20 m. Such antennas would enable high resolution ground penetrating radar studies over the long aerobot groundtracks.

The next generation of aerobots may use more efficient "pumpkin" balloon (Figure 7) design



Figure 7. "Pumpkin" balloon

which is under development in the GSFC-lead Ultra-Long Duration Balloon Program (ULDB)⁽⁷⁾. The "pumpkin" design exploits an idea of using lobed (or net) structure to increase the local curvature of balloon film and to increase an

acceptable level of superpressure without strengthening of film itself (stress in the material $T \sim dP \cdot R$, where dP is superpressure and R – local radius of curvature). Most of load is bearing by the load lines ("tendons"). Recent progress in balloon analysis, fabrication technology and materials, especially commercial availability of high-strength polybenzoxazole (PBO – commercial name Zylon[®]) fiber, resulted in development and successful stratospheric test flight of the first ULDB balloon⁽⁸⁾.

Martian aerobots should operate at temperatures down to 140 °K i.e. 70 degrees lower than in the Earth stratosphere. Polyethylene - base material used in the ULDB balloon becomes brittle at this temperature and other materials and method of fabrication are under development to implement "pumpkin" technology for Martian missions.

7. COMMUNICATIONS

Even with on-board compression aerobots virtually can provide practically unlimited amount of high-resolution data during their multi-day flight. Capability of communication is the most limiting factor for the science data return.

Both ways of increase of data volume should be pursued – increase of data rate between aerobot and orbiter and increase of time of transmission periods. Global communication coverage is essential to exploit all advantages of long-duration flights during which aerobot could traverse over wide range of latitudes and longitudes. Only areas of high Martian volcanoes are inaccessible for aerobots.

Different factors should be considered for design of aerobot communication system. Mass, power, energy, antenna, data rate and data volume per day are of prime concern. Mass constraints make impractical direct-to-Earth (DTE) link for data transmission though DTE could be used to receive a Doppler pattern during EDI phase.

Orbiters on circular polar orbits provide best fit for aerobots since they support communications over the entire planet. The orbiter altitude affects communications in several ways.

If we assume that power of the aerobot transmitter is limited by some value (realistically approximately 1 W for aerobots of the first generation and 5-10 W for the next generation) and that antenna radiates isotropically in an upper hemisphere than, obviously, higher orbits result in increase of range and decrease of data rate while the volume of transmitted data varies less significantly. Figure 8 shows some trades of the communication system.

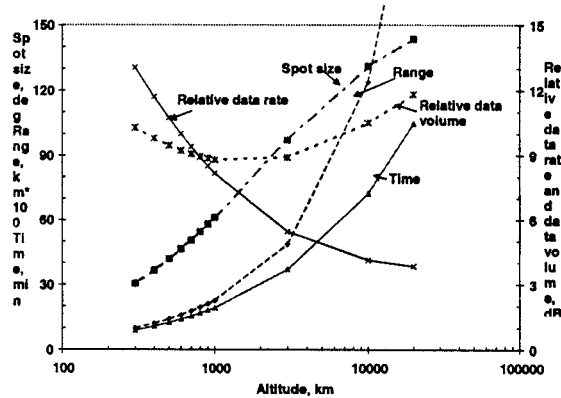


Figure 8. Trades in aerobot communications

All data are calculated for a minimum elevation angle of 10° from aerobot to orbiter (or 80° nadir angle from orbiter). It is assumed that the orbiter antenna has a matched pattern and radiates uniformly within a cone of angle θ limited by a visible disk of Mars. The areocentric spot size is limited by a circle of 80° nadir angle. Time τ is a period needed for the spot to pass over an aerobot. Relative data rate is proportional to a product G_o/D^2 or $(\lambda/D \cdot \theta)^2$ where G_o – gain of the orbiter's antenna, D – range, λ – wavelength, θ – cone angle of the orbiter's antenna. Relative data volume is product of data rate by time of one pass τ .

Since antenna on the orbiter is assumed to have a matched pattern, the data rate decreases 2.5 times when altitude increases from 300 km to 3000 km. Data volume per pass decreases only 13% but twice more energy is required for transmission. Further increase of altitude to 17,000 km results in growth of data volume by 10% compared to 300-km orbit whereas the required transmission time increases 10 times.

When antenna gains are fixed on both ends of the link, the received power and data rate increase as a square of wavelength. Increase of wavelength

needs increase of antenna size both on an aerobot and on an orbiter; mass and structural requirements will limit the wavelength.

Communication opportunities is another factor. Figure 9 shows periods of visibility (within nadir angle 80°) between orbiter and aerobot at the

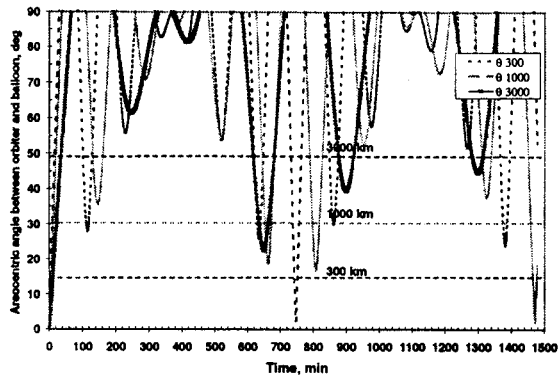


Figure 9. Communication periods for orbiter altitude 300, 1000 and 3000 km

equator during one sol for three altitudes of orbit – 300, 1000 and 3000 km. It is assumed that at time $t=0$ the orbiter is directly above the aerobot. The plotted parameter is an areocentric angle between the orbiter and the aerobot, dashed horizontal lines show boundary of 80° nadir angle visibility zone for the appropriate orbit altitude. The equatorial site is the worst case – visibility periods occur more often with increase of latitude and near the pole the aerobot can communicate with orbiter at every orbit.

For 300 km orbit there are two major communication periods – one during the day and another during the night – both about 9 min long. For 1000 km there are three 20 min periods and for 3000 km – four periods about 60 min long. It provides an opportunity to transmit 1.5-2 times more data than from 300-km orbit.

During daytime the energy required for data transmission and accordingly the length of transmission period is not critical since the aerobot transmitter can be powered directly from a solar array. Night-time transmissions are run from batteries, and increase of energy requires a proportional increase in mass of batteries. Associated mass penalty, especially for orbits above 1000 km, could be a too high price for increase of data volume. Other considerations such as number of communication orbiters, number of other surface stations which heed to

be provided with communication, time allocations both on orbiter and aerobot will also influence design of communication system.

8. SUMMARY

The developing planetary aerobot technology makes possible first small-scale focused science aerobot mission to Mars in 2005. Acquired flight experience and further technology progress will enable the next generation of ultra-long duration aerobots with composite set of instruments for high-resolution high-sensitivity studies of surface and subsurface of the large areas of Mars.

9. ACKNOWLEDGEMENTS

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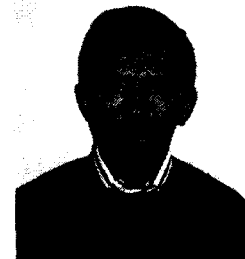
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Viktor V. Kerzhanovich is a Principal member of Technical Staff at JPL. He received his B.S. in physics from Moscow State University, Candidate of Science degree and Doctor of Science degree in physics from



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